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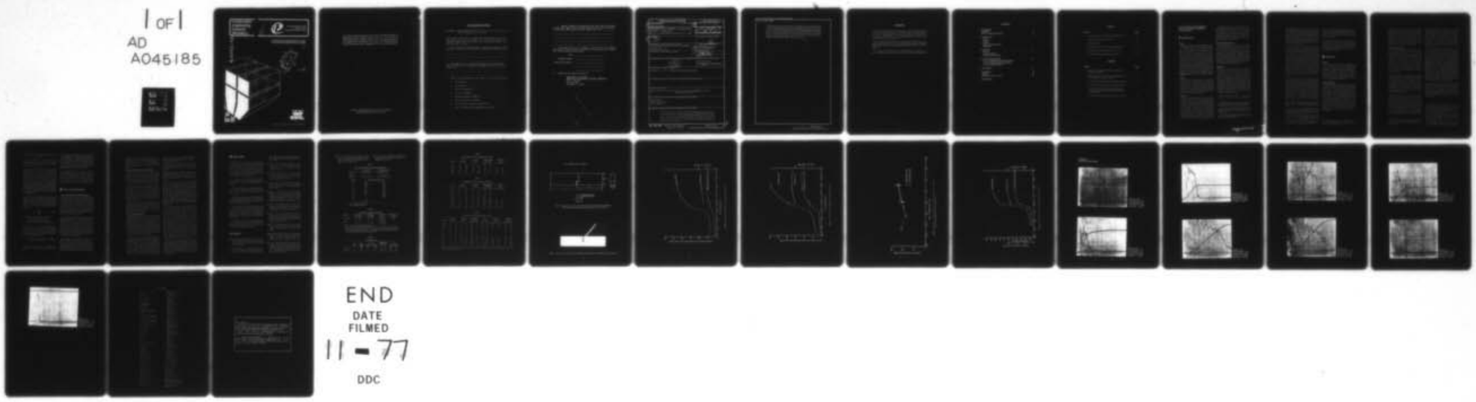

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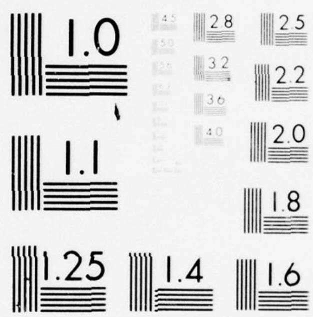

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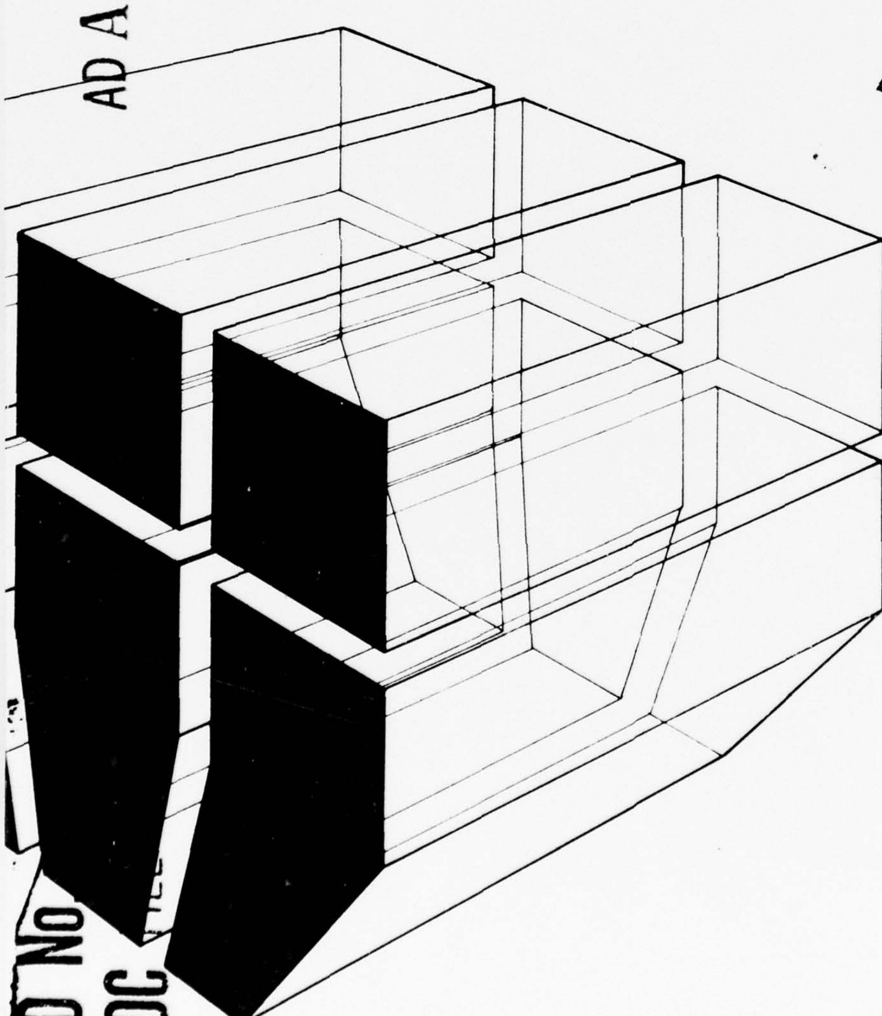
INTERIM REPORT M-227
September 1977
Engineering Criteria for Welds

THE EFFECTS OF WELD POROSITY ON THE FRACTURE TOUGHNESS OF A514F STEEL

by
E. P. Cox



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This report presents the results of an investigation conducted to evaluate the effects of clustered and linear porosity on the impact (dynamic tear) and dynamic fracture toughness of American Society for Testing and Materials (ASTM) A514 grade F steel welds. Tests were conducted using standard 1.59-cm dynamic tear specimens in a dynamic tear machine. Tests were also conducted using instrumentation recently developed for use with the dynamic tear machine.

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Results indicated that the upper shelf fracture toughness of welds containing clustered or linear porosity is sufficient to permit large-scale plastic deformation prior to fracture. However, the ductile-to-brittle transformation in welds containing linear porosity may be elevated to normal operating temperatures, thus increasing the possibility of catastrophic fracture. The instrumented dynamic tear test was found to provide a means of calculating dynamic fracture toughness values on the lower shelf and a lower bound for fracture toughness on the upper shelf in high-strength structural steels.

FOREWORD

This investigation was performed for the Directorate of Military Construction, Office of the Chief of Engineers (OCE) under Project 4A762731AT41, "Applications Engineering"; Task 04, "Engineering Criteria for Design and Construction"; Work Unit 011, "Engineering Criteria for Welds." The applicable QCR number is 1.06.004. The OCE Technical Monitor was Mr. I. A. Schwartz.

The investigation was performed by the Metallurgy Branch (MSM), Materials and Science Division (MS) of the U.S. Army Construction Engineering Research Laboratory (CERL). CERL personnel directly involved with this study were Mr. E. P. Cox and Mr. F. H. Kisters.

Dr. A. Kumar is Chief of MSM and Dr. G. R. Williamson is Chief of MS. COL J. E. Hays is Commander and Director of CERL and Dr. L. R. Shaffer is Technical Director.

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THE EFFECTS OF WELD POROSITY ON THE FRACTURE TOUGHNESS OF A514F STEEL

1 INTRODUCTION

Problem

Many of the Corps of Engineers' metallic structures are fabricated by welding, and preventing brittle fracture of these structures is very important. Various types of discontinuities and defects sometimes introduced into welds during fabrication (such as cracks, porosity, and lack of penetration) have been shown to cause premature brittle fracture in structural steel weldments. Thus, when such defects are detected, they are usually removed to insure the structural integrity of the joint. However, not all discontinuities are detected nor are they always eliminated during service. Of particular interest are porosity defects—both uniformly distributed and clustered. Little experimental research has been conducted on the effects of porosity on the toughness and ductile-to-brittle transition temperature (DBTT) of high-strength, low-alloy (HSLA) steels (the **Background** section reviews the available literature).

Objective

The purpose of this investigation was to evaluate the effects of clustered and linear porosity on the impact (dynamic tear) and dynamic fracture toughness of American Society for Testing and Materials (ASTM) A514 grade F steel welds. This investigation provides a partial basis for evaluation inspection criteria relating allowable defect parameters to given levels of weldment mechanical properties performance.

Approach

Welds containing controlled amounts of clustered and linear porosity were made and fabricated into standard 1.59-cm dynamic tear specimens (Figure 1). Specimens containing clustered porosity were prepared and machine-notched so that the cluster was located at the notch root. Linear porosity specimens had the porosity aligned at the notch and along the fracture path. All welds were inspected by x-ray radiography prior to machining to determine their adequacy for subsequent testing. The specimens were tested at temperatures ranging from −190°C to +100°C. The fracture surfaces were visually examined after testing.

The dynamic toughness of weld metal adjacent to the heat-affected zone along the line of fusion was also tested using instrumentation recently developed for the dynamic tear machine. Load vs. time was recorded for specimens notched in the fusion zone. Using these data, dynamic fracture toughness values were calculated. The test temperatures for these specimens ranged from −140°C to +21°C.

Mode of Technology Transfer

The information in this report is part of a long-term research effort designed to improve Corps of Engineers guide specifications concerned with the accept/reject levels of weld defects. Pertinent standards selected for upgrading are: Corps of Engineers Guide Specification CE-260.02, *Guide Specification for Military Construction: Welding, Structural, for Critical Applications* (June 1968); Federal Construction Guide Specification Section 05141, *Welding, Structural* (November 1974); and Federal Construction Guide Specification Section 15116, *Welding, Mechanical* (May 1974).

Background

Review of the effects of porosity on weldment mechanical properties by Pense and Stout[1] indicated that scattered porosity had no effect on tensile strength unless it was "excessive." No indication was given of the amount of porosity that was considered to be excessive or of the quantities of porosity in the welds. In a more recent investigation of the effects of uniformly distributed porosity on the tensile strength of aluminum alloy weldments, Lawrence and Munse[2] noted that visible porosity was often accompanied by significant amounts of invisible micro-porosity. Their results indicated that tensile strength and ductility gradually decreased in proportion to the amount of total porosity present on the fracture surface.

Lundin[3] has recently completed a review of the literature on the effects of weld discontinuities on

[1] A. W. Pense and R. D. Stout, "Influence of Weld Defects on the Mechanical Properties of Aluminum Alloy Weldments," *Welding Research Council Bulletin*, No. 152 (July 1970).

[2] F. V. Lawrence, Jr. and W. H. Munse, "Effects of Porosity on the Tensile Properties of 5083 and 6061 Aluminum Alloy Weldments," *Welding Research Council Bulletin*, No. 181 (February 1973).

[3] C. D. Lundin, "The Significance of Weld Discontinuities: A Review of Current Literature," *Welding Research Council Bulletin*, No. 222 (December 1976).

mechanical properties. The section concerning porosity in ferritic steels indicated that many researchers have found that scattered, unaligned, and unclustered porosity in amounts less than 7 percent had an insignificant influence on yield strength, tensile strength, slow bend ductility, and reduction in area. Internal porosity was observed to be less harmful than surface or near-surface porosity, while aligned or clustered porosity was found to be a severe stress concentrator.

Clustered porosity in A514F butt weld specimens pulled in tension has been investigated by Honig and Carlson.[4] Their research indicated that clustered porosity severely reduced ductility when present in amounts of 1 percent or more of the theoretical cross-sectional area, and that the tensile strength decreased 8 percent for porosity levels greater than 6 percent. The slight reduction in strength indicated that porosity in certain amounts can be tolerated under static loading, but because of the drastic loss of ductility, it is unacceptable for use in limit-load-designed structures. Similar tests on A514F weldments were conducted by Lawrence, Radziminski, and Kruzic.[5] No reduction in tensile strength was noted for amounts of clustered porosity of less than 4 percent; however, 1 percent porosity caused the strain at fracture to decrease from 20 to 9 percent.

Very little research has been conducted on the impact toughness (a material's characteristic ability to resist fracture under an impact load) of welds containing porosity. One such investigation was conducted by Green, Hamad, and McCauley[6] on AISI 1020 steel. Their work on submerged arc welds showed a decrease in impact energy proportional to the percentage of distributed porosity on the fracture surface. Similar results were found for GMA welds for distributed porosity levels of up to 3 percent. The results of Charpy V-notch impact tests on A514F steel conducted by Bradley and McCauley[7] showed no decrease in impact energy for distributed porosity levels as high as 5 percent on the cross section. Submerged arc welds were unaffected to 5 percent cross section porosity, but a rapid decrease in impact energy occurred for greater amounts of porosity.

The general consensus of sources investigated in Lundin's literature review[8] is that porosity in amounts less than 5 percent has little effect on Charpy V-notch toughness and, for welds with greater amounts, the impact behavior is a function of the percentage of the area occupied by the porosity.

2 PROCEDURE

Materials

The base metal used in this study was ASTM A514 grade F steel (U. S. Steel T-1), an extra-high-strength, low-alloy structural steel suitable for weld fabrication. Since this is a quenched and tempered steel, its microstructure is comprised of tempered martensite and tempered bainite. The welding electrode used was Airco AX110, 0.16-cm bare wire electrode. Tables 1 and 2 give the chemical compositions and mechanical properties of the base and weld metals.

Specimen Fabrication

Welded specimens were fabricated from large specimen blanks of A514F steel plate. The specimen blanks were saw-cut in half, and 60 degree double V bevels without root faces (lands) were machined. The specimen blanks were butted together and preheated to 93.3°C. Welding was done by the gas metal arc (GMA) process; Table 3 gives the welding parameters used. Clustered porosity was induced into the weld metal by momentarily interrupting the shielding gas on the first pass and then using sound weld cover passes. Linear porosity specimens were fabricated similarly. After welding, the specimen blanks were x-ray radiographed to insure that the welds were suitable for testing and to locate weld porosity for specimen layout and machining.

[4] F. M. Honig, Jr. and K. W. Carlson, "Tensile Properties of A514F Steel Butt Joints Containing Cluster Porosity," *Welding Journal*, Vol 55, No. 4 (1976), Research Supplement, pp 103s-107s.

[5] F. V. Lawrence, Jr., J. B. Radziminski, and R. W. Kruzic, *The Effect of Porosity on the Static Tensile Behavior of High Strength Structural Steel Weldments*, Technical Report UILU-ENG-71-2024 (University of Illinois, 1971).

[6] W. L. Green, M. F. Hamad, and R. B. McCauley, "The Effects of Porosity on Mild Steel Welds," *Welding Journal*, Vol 37, No. 7 (1959), Research Supplement, pp 209s-306s.

[7] J. W. Bradley and R. B. McCauley, "The Effects of Porosity in Quenched and Tempered Steel," *Welding Journal*, Vol 43, No. 9 (1964), Research Supplement, pp 408s-414s.

[8] C. D. Lundin, "The Significance of Weld Discontinuities: A Review of Current Literature," *Welding Research Council Bulletin*, No. 222 (December 1976).

Specimens were machined in accordance with MIL-STD-1601 (SHIPS).[9] Figure 1 shows the machine-notched specimen dimensions. The clustered porosity specimens were machined so that the porosity was located at the notch root, while the linear porosity specimens were machined with the porosity aligned along the fracture path. The specimen faces were surface-ground to provide a smooth surface and to insure that they were parallel or perpendicular.

Dynamic Tear (DT) Testing

The DT specimens were fractured by impact loading in a *Southwest Research Institute 2710-J capacity*, double-pendulum dynamic tear machine. The specimens were fractured at temperatures ranging from −190°C and +100°C. The DT specimens had thermocouples micro-spot-welded close to the notch and connected to a digital voltmeter; temperature was monitored by direct readout of the thermocouple. To obtain the desired test temperature, the specimens were either warmed from liquid nitrogen temperature or cooled from an elevated temperature. Figure 2 shows the location of the thermocouple on a specimen prepared for testing.

After testing, the specimen halves were warmed to room temperature in a double chamber bath, with acetone in one chamber and surrounding warm water in the other. This prevented condensation of water and, consequently, corrosion on the fracture surfaces of specimens tested below room temperature. The fracture surfaces were then dried, sprayed with a clear lacquer, marked, and taped together. Fracture surfaces were examined after testing was completed, and all surface irregularities were noted.

Weld metal specimens were impact-tested at various temperatures to obtain data on the energy absorbed in fracturing the DT specimen (henceforth referred to as the fracture energy [FE] or DT energy). Many structural steels and welds exhibit an abrupt change in fracture energy as the test temperature is decreased below room temperature. The temperature spread over which a rapid change from a relatively high fracture energy (upper shelf energy) to a much-reduced fracture energy (lower shelf energy) occurs is known as the ductile-to-brittle transition temperature (DBTT) range. The DBTT in steels is very sensitive to specimen dimensions, loading rate, microstructure, and notch acuity. Charpy V-notch specimens can be used to locate the DBTT in very high-strength, low-toughness steels; however, such specimens often do not adequately describe the toughness change occurring in lower strength structural steels. Charpy impact tests on thick plate steels sometimes gives results unrepresentative of the plate, hence indicating the necessity for larger specimens.

The 1.59-cm dynamic tear specimen has been found to give adequate data on heavy section structural steels. The DBTT is well defined in this test. The dynamic tear test has also been correlated with K_{Ic} fracture toughness measurements made on the upper shelf. This correlation was based on slow bend K_{Ic} tests which were compared with 2.54-cm dynamic tear specimen data.[10] In a later study conducted at the Naval Research Laboratory, a proportional relationship was found to exist between the fracture energies obtained for the 1.59- and 2.54-cm dynamic tear specimens.[11] The 2.54-cm specimens when fractured produced fracture energies eight times the values obtained from the 1.59-cm specimens. Lange and Loss[12] present a more complete discussion on dynamic tear and fracture toughness test correlations. Fracture toughness is the vehicle for relating the fracture resistance of a material to useful design parameters.

The value of the fracture toughness, K_{Ic}, obtained using the 1.59-cm DT test is based on correlations between static K_{Ic} tests and the 2.54-cm dynamic tear tests. The 1.59-cm DT and 2.54-cm DT tests are linearly related. Consequently, an equivalent value of K_{Ic} can be established from the standard 1.59-cm DT test. The relationship is given by Eq 1 for values of DT energy in ft-lb:

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[9] *Military Standard Method for 5/8-Inch Dynamic Tear Testing of Metallic Materials*, MIL-STD-1601 (SHIPS) FSC 95GP (Naval Ship Systems Command, Department of the Navy, 8 May 1973).

[10] W. S. Pellini, *Advances in Fracture Toughness Characterization Procedures and in Quantitative Interpretations to Fracture-Safe Design for Structural Steels*, NRL Report 6713 (Naval Research Laboratory, 3 April 1968) (also *Welding Research Council Bulletin*, No. 130, May 1968).

[11] T. W. Crooker and L. A. Cooley, *Fracture Toughness of Thick Steel Sections (Correlations Between 5/8-in. and 1-in. Dynamic Tear Test Energies for Steels Under Conditions of Fully Plastic Fracture)*, Report of NRL Progress (Naval Research Laboratory, June 1969).

[12] E. A. Lange and F. J. Loss, "Dynamic Tear Energy—A Practical Performance Criterion for Fracture Resistance," *Impact Testing of Metals*, ASTM STP 466 (1970), pp 241-250.

$$\text{Equivalent } K_{Ic} = 0.206\,(1.59\text{-cm DT energy}) + 86 \text{ ksi}\sqrt{\text{in.}} \qquad \text{[Eq 1]}$$

To convert to MPa $\sqrt{m}$, Eq 1 is multiplied by 1.1. This equation is valid only on the upper shelf of the DT test; no correlation has been established in the transition region or on the lower shelf.

A second and newer method of determining the dynamic fracture toughness of materials is being developed at the U. S. Army Construction Engineering Research Laboratory (CERL). The dynamic tear machine has recently been instrumented so that the magnitude of the impact loads can be obtained and recorded vs. time on an oscilloscope. Experiments to establish a reliable method of obtaining dynamic fracture toughness (K_{Id}) values are currently being performed. To date, the values of K_{Id} obtained from the instrumented test are not valid, but rather are estimates of the toughness. Parameters such as crack length, acuity, and interpretation of the load vs. time record need to be studied further.

The method of calculating the dynamic fracture toughness using the instrumented dynamic tear test required analyzing the load vs. time trace obtained. Presently, the maximum load value is being used to calculate the value of K_{Id}. Once the load point has been determined, K_{Id} can be calculated using the equation

$$K_{Id} = \frac{PSY}{BW^{3/2}} \qquad \text{[Eq 2]}$$

where P is the maximum load point in newtons
S is the specimen span = 0.165 m
B is the specimen thickness = 0.016 m
W is the specimen height (or depth) = 0.041 m

The Y parameter in Eq 2 is an expression used to account for the presence of the notch on the specimen's stiffness. The value of Y for the 1.59-cm specimen is 1.85; this value was determined using the expression for three-point bend fracture toughness testing specified in ASTM Standard E 399-74:[13]

$$Y = 2.9\,(a/w)^{1/2} - 4.6\,(a/w)^{3/2} + 21.8\,(a/w)^{5/2} - 37.6\,(a/w)^{7/2} + 38.7\,(a/w)^{9/2} \qquad \text{[Eq 3]}$$

[13] "Plane-Strain Fracture Toughness of Metallic Materials," ASTM E 399-74, *ASTM Annual Book of Standards*, Part 10 (1976).

The assumption that instability and crack extensions occur at maximum load is generally accepted; hence, in calculating K_{Id} the maximum load point is used. The user should be cautioned that in the presence of large-scale plasticity, the value of K_{Id} calculated using this method tends to be overly conservative; that is, this K_{Id} does not reflect the additional energy expended in plastic deformation prior to failure.

Weld metal dynamic tear specimens for testing on the instrumented dynamic tear machine were fabricated using a K-groove joint preparation. The use of the K-groove joint results in both a linear fusion and a linear heat-affected zone through the plate thickness, which facilitates evaluation of the toughness in this area. The welding parameters used are given in Table 3.

3 RESULTS AND DISCUSSION

DT Tests of Welds Containing Clustered Porosity

Table 4 presents the results of the DT tests of welds containing clustered porosity. The dial energy (or fracture energy) obtained from the standard DT test is the total energy to fracture the specimen, which includes the inertial energy of accelerating the test specimen after fracture. These data were further reduced by dividing the fracture energy by the net (unflawed) fracture area. Equivalent K_{Ic} fracture toughness values were calculated using Eq 1. These data are plotted as a function of temperature in Figure 3.

The specimens containing clustered porosity show high fracture energies on the upper shelf (400 to 500 J). When the fracture energy is divided by the net unflawed area of the specimen, the scatter in the data is reduced. These data indicate that the energy absorbed in fracturing the specimen is a function of the net section area on the upper shelf. If this can be further substantiated, it means that weld porosity in clusters is a benign discontinuity and does not reduce the toughness on the upper shelf, but serves only to reduce the total cross-sectional area.

The Equivalent K_{Ic} values shown in Figure 3 are toughness values for clustered porosity; that is, the clusters were located at the notch root and therefore served as the crack initiation defect. These values were calculated using Eq 1 and are estimates of the fracture toughness rather than true measured values. The welds containing the clustered porosity have high toughness

(approximately 175 MPa $\sqrt{m}$), indicating good fracture resistance in the upper shelf. Failure of a weld on the upper shelf would only occur after considerable plastic deformation. Brittle fractures are possible below the ductile-to-brittle transition, i.e., temperatures below -40°C.

DT Tests of Welds Containing Linear Porosity

Table 5 presents the DT data for specimens containing linear porosity. Analysis of the specimen results consisted of (1) measuring the dynamic tear fracture energy as a function of temperature, (2) dividing the fracture energy by the net section area, and (3) calculating Equivalent K_{Ic} fracture toughness values using Eq 1. These data are plotted vs. temperature in Figure 4.

The fracture energy decreased rapidly between +20° and -80°C. Insufficient data are available to discern the transition more exactly; however, the data do indicate that the range of the ductile-to-brittle transition may be elevated to normal operating temperatures. The fracture energy per unflawed (net) area takes into account the size effect of the linear porosity. This curve in Figure 4 indicates the same broad transition regardless of the defect size.

Values of Equivalent K_{Ic} were calculated using Eq 1. These data shown in Figure 4 reveal that the welds have good upper shelf toughness and the toughness remains high at temperatures down to -40°C. Failure of a weld on the upper shelf would only occur after considerable plastic deformation.

DT Tests on Weld Fusion Zone

These specimen tests were conducted using the instrumented tup on the dynamic tear machine. Outputs from this system are the dynamic load vs. time response during testing and the dial energy at fracture. Equivalent K_{Ic} values were calculated using Eq 1, the fracture energy was divided by net area, and K_{Id} values were calculated using Eq 2 and the load vs. time curves shown in the appendix. Figure 5 presents a graph of these data. Figure 6 shows a plot of the fracture energy vs. test temperature. The data obtained for the weld fusion zone specimens are given in Table 6.

The fusion zone of specimens fabricated using the weld parameters specified in Table 3 exhibited an upper shelf fracture energy of approximately 950 J at 21°C. The upper shelf fracture energy will be different for other welding parameters; this effect is being studied in a related study of the weldability of construction materials. This upper shelf fracture energy decreased rapidly for test temperatures below 21°C, and in the temperature range between -40°C and -60°C, the average fracture energy decreased from about 750 J to about 225 J. The limited amount of data prevents inferring more than that toughness decreases significantly below -40°C.

Similar trends occurred when the fracture energy values were divided by the net area of the test specimen. These data are also plotted vs. test temperature in Figure 6.

Equivalent K_{Ic} values computed using Eq 1 are plotted in Figures 5 and 6. The upper shelf K_{Ic} values indicate that the weld metal fusion zone is very tough and gross section plasticity is anticipated prior to fracture.

As the load vs. time curves shown in the appendix indicate, severe dynamic load oscillations occur during fracture as the specimen vibrates. The load oscillations decrease as the test temperature decreases. Specimen H-6 tested at -140°C has a load record which is essentially elastic, indicating complete fracture of the specimen prior to any detectable vibration; i.e., fracture had occurred within one period of oscillation. As the test temperature increases, the time to fracture and the amount of plasticity increases, so that the load-time records show more oscillations. These oscillations are clearly seen on the load-time record for specimen H-8.

The actual load response occuring during fracture can be traced by noting the mean values between the peaks and connecting these points with a smooth curve. To calculate a value of K_{Id} from these data, the maximum load point was chosen for P in Eq 2. Since all fractures were elastic-plastic at test temperatures above the lower shelf, the calculated K_{Id} values for the transition region and upper shelf are conservative; that is, they do not account for the plastic deformation which occurred during fracture. The state-of-the-art technology has not yet advanced to the point where the load vs. time curves showing large-scale plasticity can be interpreted accurately. However, for the high-strength structural steels, K_{Id} values for the upper shelf obtained from an instrumented dynamic tear test do provide a lower bound for the fracture toughness. Hence, the test can be a useful engineering tool for screening purposes.

Figure 5 shows the calculated K_{Id} values obtained from the instrumented dynamic tear test as a function of test temperature. The Equivalent K_{Ic} values derived from empirical data are also shown for comparison. As can be seen, the calculated K_{Id} values are conservative compared to the Equivalent K_{Ic} values. This is consistent with the elastic-plastic fracture phenomenon discussed above.

4 CONCLUSIONS

The following conclusions were drawn based on the data obtained from the dynamic tear tests conducted on welds containing clustered porosity located at the notch root and linear porosity located along the fracture path, and from weld metal fusion zone tests. These conclusions are based on the results for one set of welding parameters; changing these parameters may produce significantly different results.

1. The upper shelf fracture toughness (Equivalent K_{Ic}) is sufficient in welds containing clustered porosity to permit large-scale plastic deformation prior to fracture.

2. The upper shelf fracture toughness (Equivalent K_{Ic}) of welds containing linear porosity is also sufficient to cause large-scale plastic deformation prior to fracture.

3. The ductile-to-brittle transition temperature range in welds containing linear porosity may be elevated to normal operating temperatures, thus increasing the possibility of a catastrophic fracture.

4. The instrumented dynamic tear test can be used to calculate dynamic fracture toughness (K_{Id}) values on the lower shelf. In the transition region and on the upper shelf, the load vs. time curves show large-scale plasticity present during fracture; consequently, the K_{Id} values (determined using Eq 2) in these areas are conservative.

5. K_{Id} values obtained on the upper shelf can be used for engineering purposes to prevent brittle fracture, since they represent a lower bound for fracture toughness in high-strength structural steels.

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Table 1

Chemical Composition of Base Metal and Welding Electrode

	Base Metal*	Welding Electrode**
Manufacturer	U.S. Steel Corporation	Air Reduction Co., Inc.
Designation	T-1	Airco AX-110
Thickness	3/4 in. (1.91 cm) plate	1/16 in. (0.16 cm) base wire
Element	**Chemical Composition, wt %**	
C	0.15	0.084
Mn	0.89	1.54
P	0.009	0.008
S	0.027	0.008
Si	0.27	0.45
Ni	0.90	2.43
Cr	0.52	0.049
Mo	0.42	0.48
V	0.06	0.008
Al	–	0.0075
Ti	–	0.004
Zr	–	–
B	0.0015	–
Cu	0.21	–

*Data from independent analysis.
**Data supplied by manufacturer.

Table 2

Tensile Properties of Base Metal and Weld

Material	Tensile Strength ksi	Tensile Strength MPa	Yield Strength ksi	Yield Strength MPa	Elongation percent	Reduction in Area percent
Base Metal*	120	827	113	779	36 in 2 in. (5.08 cm)	66.4
Weld**	140	965	126	869	50+ in 3/4 in. (1.91 cm)	–

* Properties of base metal provided by manufacturer.
**Average of three specimens taken from weld metal (from F. V. Lawrence, Jr., E. P. Cox, and E. M. Honig, Jr., *Influence of Heat Input and Lack of Penetration Length on the Static Tensile Behavior of High Strength Structural Steel Weldments*, Technical Report M-135/ADA012730 (U.S. Army Construction Engineering Research Laboratory, June 1975).

Table 3

Welding Parameters

	Voltage V	Current amps	Travel Speed in./min	Travel Speed cm/min	Interpass and Preheat Temp. °F	Interpass and Preheat Temp. °C	Heat Input kJ/in.	Heat Input kJ/cm
First Pass	20	330	10	25.4	200	93	39.6	15.6
Second Pass	30	330	15	37.5	200	93	26.4	10.4

Table 4

Test Results for Specimens Containing Clustered Porosity

Specimen	Test Temperature °F	Test Temperature °C	Fracture Energy ft-lb	Fracture Energy J	Fracture Energy / Net Area ft-lb/in.²	Fracture Energy / Net Area J/cm³	Equivalent K_{Ic} ksi $\sqrt{in.}$	Equivalent K_{Ic} MPa $\sqrt{m}$
CPC-2	-310	-190	57	77	86	18		
CPC-5	76	-60	235	319	354	75		
CPD-1	40	40	238	323	361	76	134	147
CPD-3	+ 86	+ 30	304	412	539	113	147	162
CPC-8	+ 86	+ 30	356	483	530	111	158	174
CPD-5	+212	+100	357	484	534	112	158	174

Table 5

Test Results for Specimens Containing Linear Porosity

Specimen	Test Temperature °F	Test Temperature °C	Fracture Energy ft-lb	Fracture Energy J	Fracture Energy / Net Area ft-lb/in.²	Fracture Energy / Net Area J/cm³	Equivalent K_{Ic} ksi $\sqrt{in.}$	Equivalent K_{Ic} MPa $\sqrt{m}$
COE-6	-310	-190	52	71	82	16	–	–
COE-8	-220	-140	59	80	93	19	–	–
COE-2	-130	- 90	93	126	146	29	–	–
COE-9	- 76	- 60	229	11	489	98	–	–
COE-4	- 76	- 60	277	376	673	135	–	–
COE-7	- 40	- 40	271	367	716	144	142	156
COE-10	- 40	- 40	284	385	689	138	145	159
COE-5	+ 86	+ 30	436	591	1058	213	176	193
COE-11	+212	+100	381	517	1105	222	164	181

Table 6

Test Results from Instrumented Dynamic Tear Tests

Specimen*	Test Temperature °F	Test Temperature °C	Fracture Energy ft-lb	Fracture Energy J	Fracture Energy / Net Area in lb/in²	Fracture Energy / Net Area J/cm²	Max Load kip	Max Load KN	Equivalent K_{Ic} ksi $\sqrt{in.}$	Equivalent K_{Ic} MPa $\sqrt{m}$	Calculated K_{Id} ksi $\sqrt{in.}$	Calculated K_{Id} MPa $\sqrt{m}$
A514F	70	21	507	687	8653	151	20.4	90.7	190	209	>194	>213
COE-3	70	21	437	593	1117	236	19.2	85.4	176	194	>183	>201
H-6	-220	-140	57	77	1314	17	20.8	92.5	–	–	>198	>218
H-7	-130	- 90	91	123	2099	27	16.8	74.7	–	–	>160	>176
H-2	- 76	- 60	130	176	3004	39	–	–	–	–	–	–
H-1	- 76	- 60	219	297	5069	65	18.6	82.7	–	–	>177	>194
H-9	- 40	- 40	601	815	10257	180	19.2	85.4	210	231	>183	>201
H-3	- 40	- 40	506	686	8636	151	20.6	91.6	190	209	>196	>215
H-8	70	21	785	1064	13397	235	23.2	103.2	248	272	>221	>243
H-4	70	21	618	838	10547	185	22.6	100.5	213	235	>215	>236

*Specimen A514F is a base metal DT test, specimen COE-3 contains linear porosity, and specimens H-1 through H-9 are tests of weld metal near the HAZ in the fusion zone.

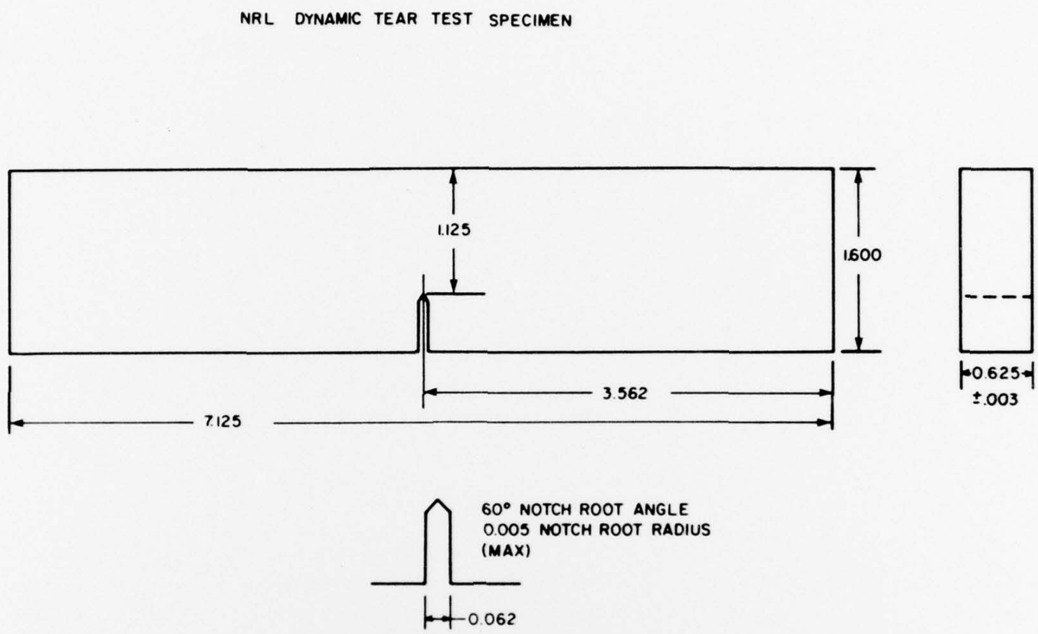


Figure 1. Standard 1.59-cm dynamic tear specimen as specified in MIL-STD-1601 (SHIPS). (All dimensions are in inches; metric conversion factor: 1 in. = 2.54 cm.)

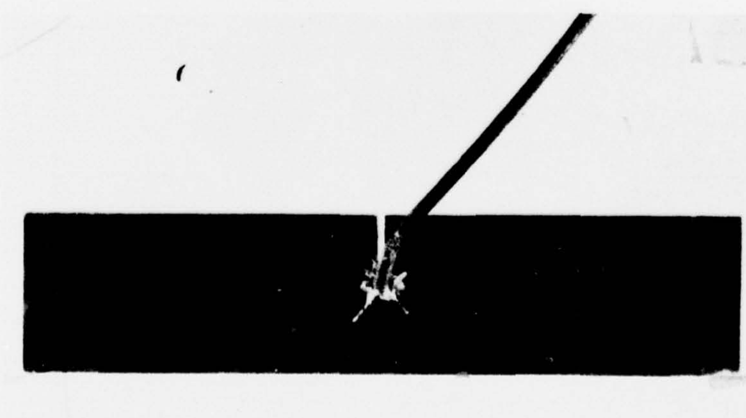


Figure 2. Dynamic tear specimen with iron-constantan thermocouple micro-spot-welded across the notch root.

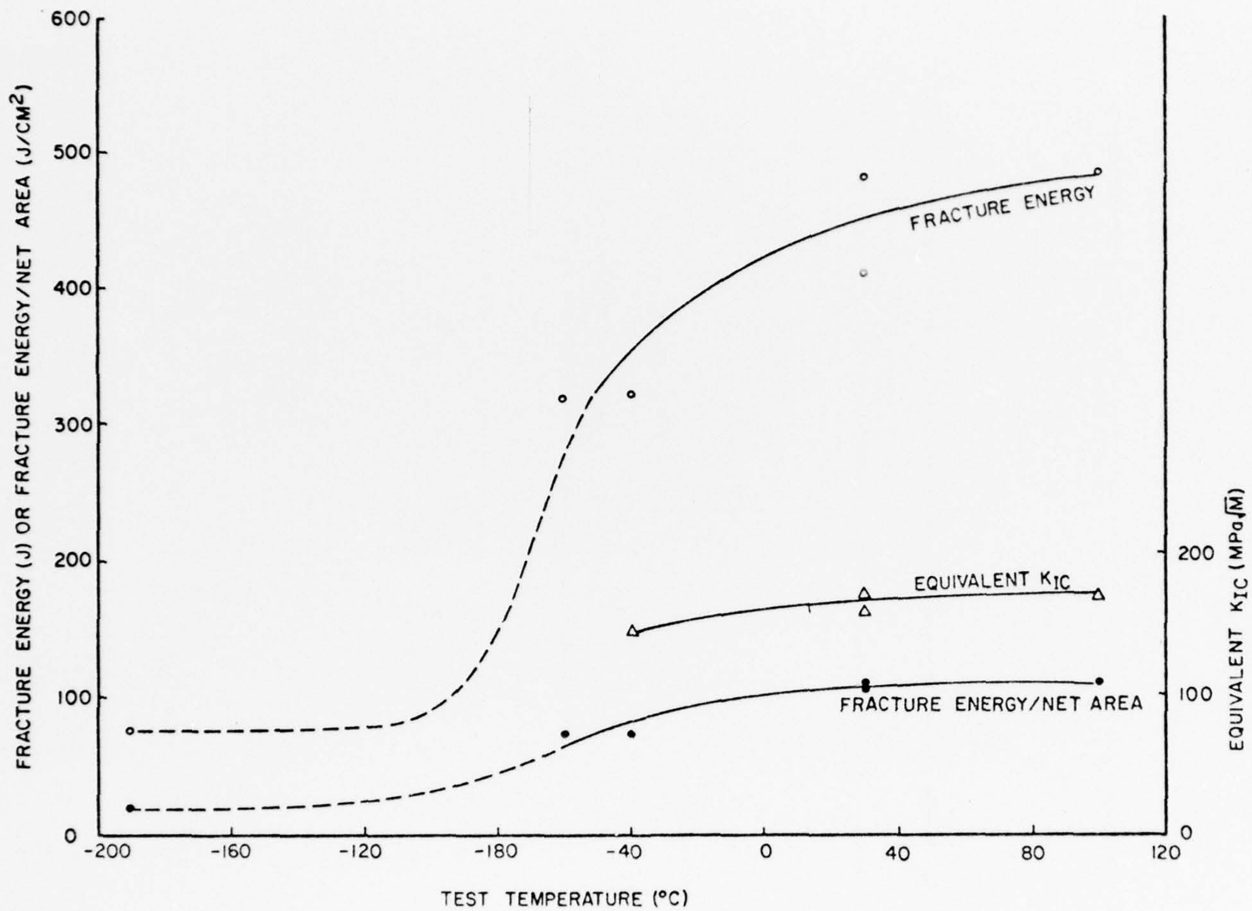


Figure 3. Test results for weld specimens containing clustered porosity.

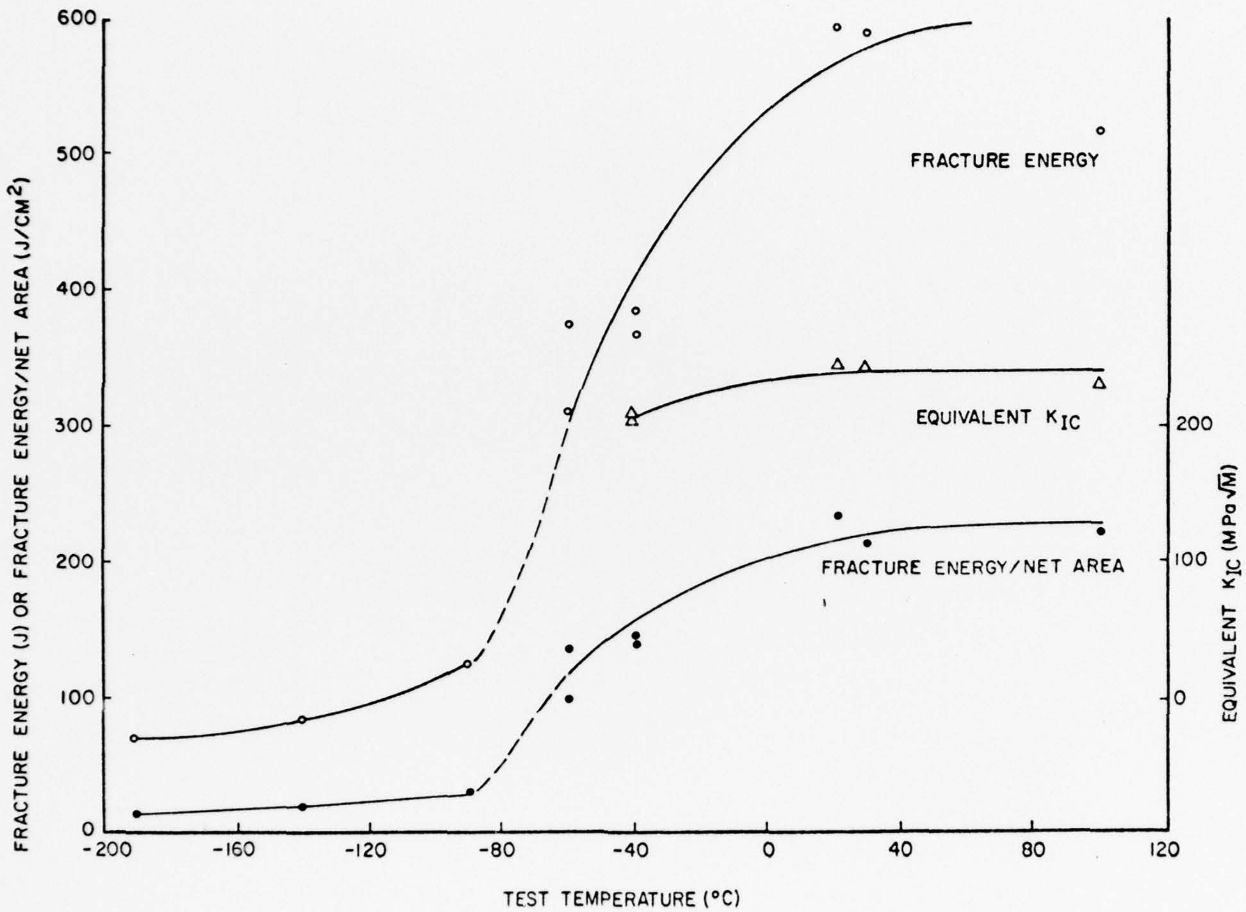


Figure 4. Test results for weld specimens containing linear porosity.

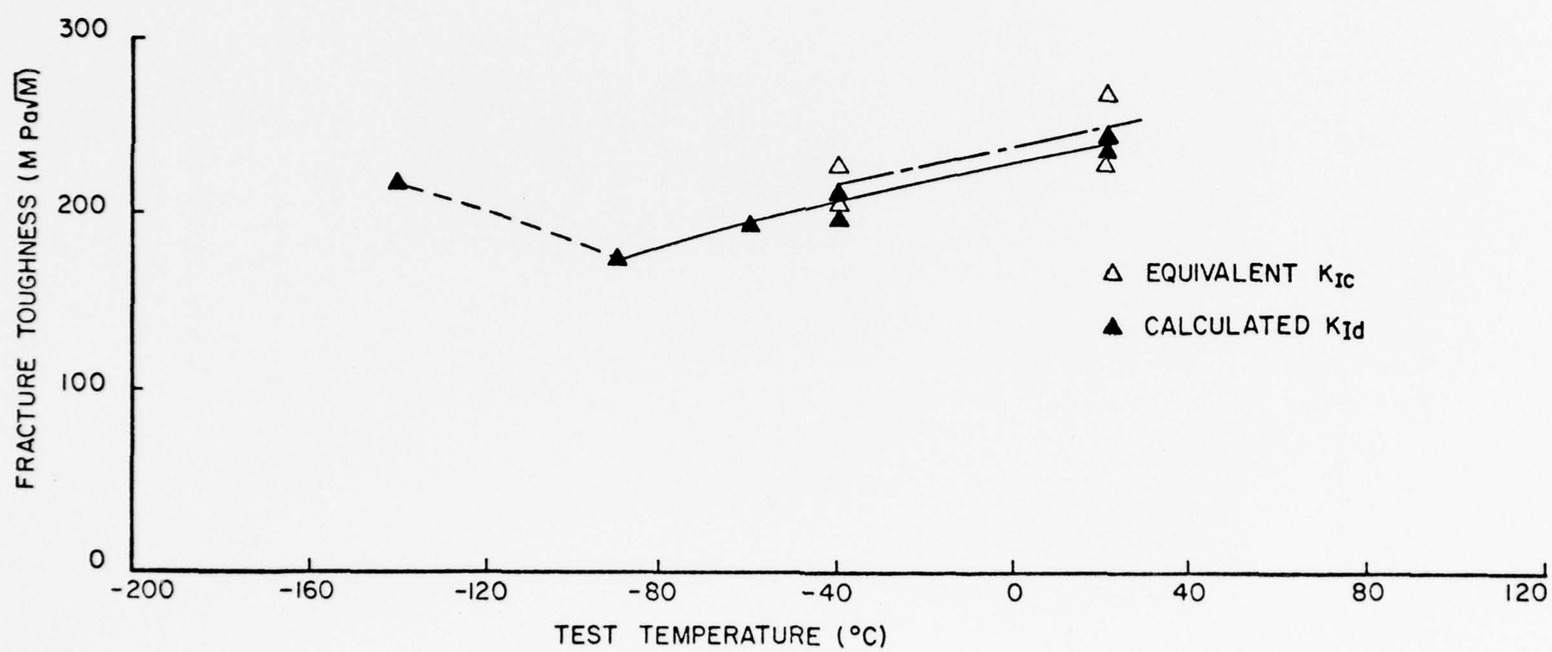


Figure 5. Comparison of empirical K_{Ic} and calculated dynamic K_{Id} fracture toughness values in weld specimens fractured in the fusion zone.

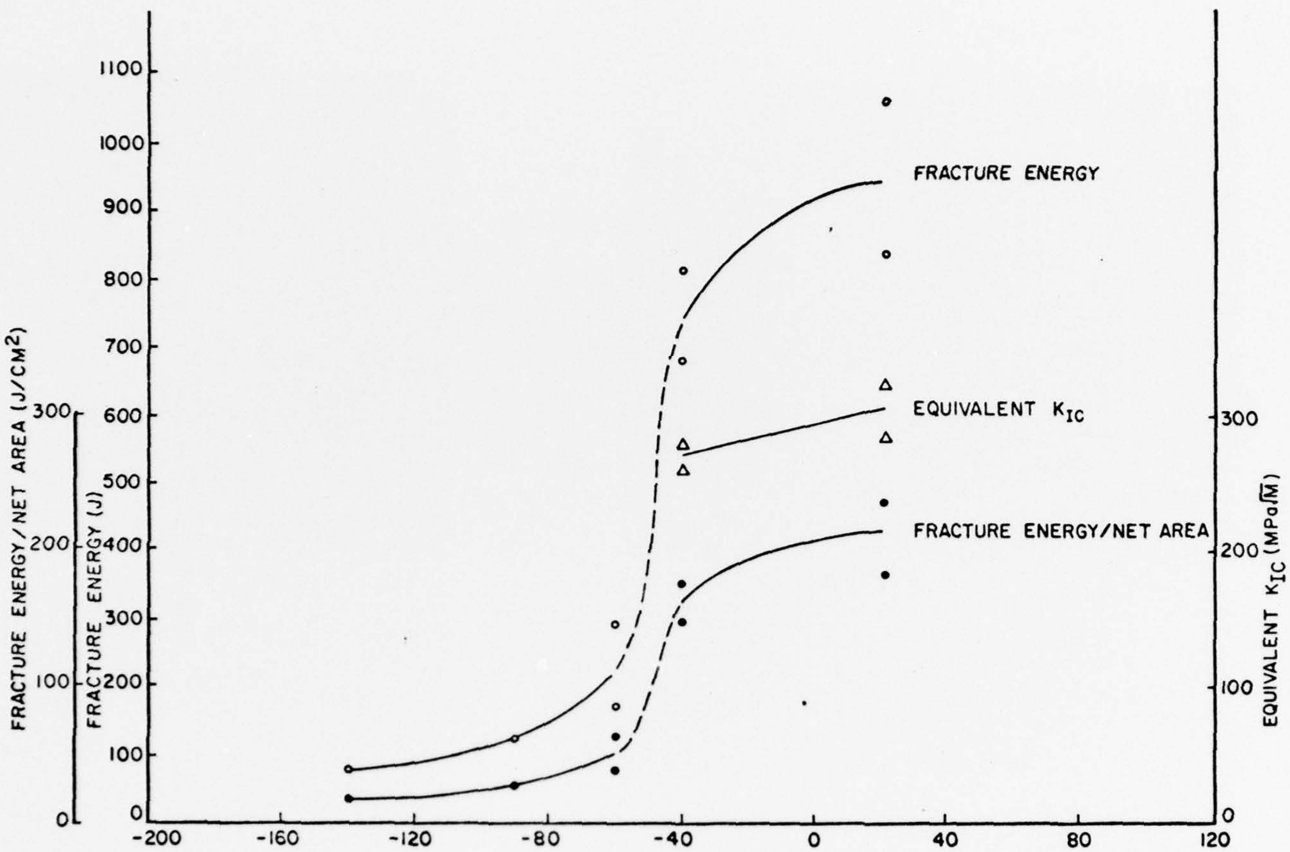
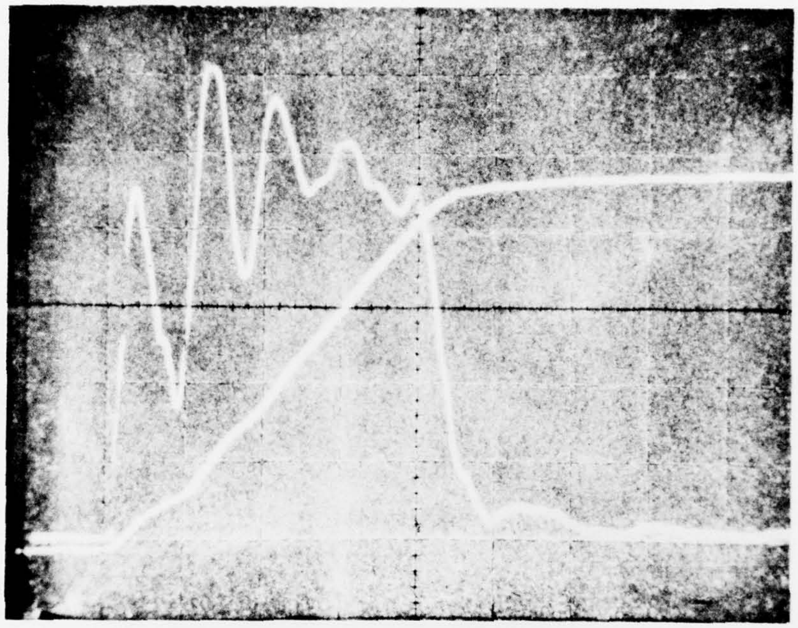
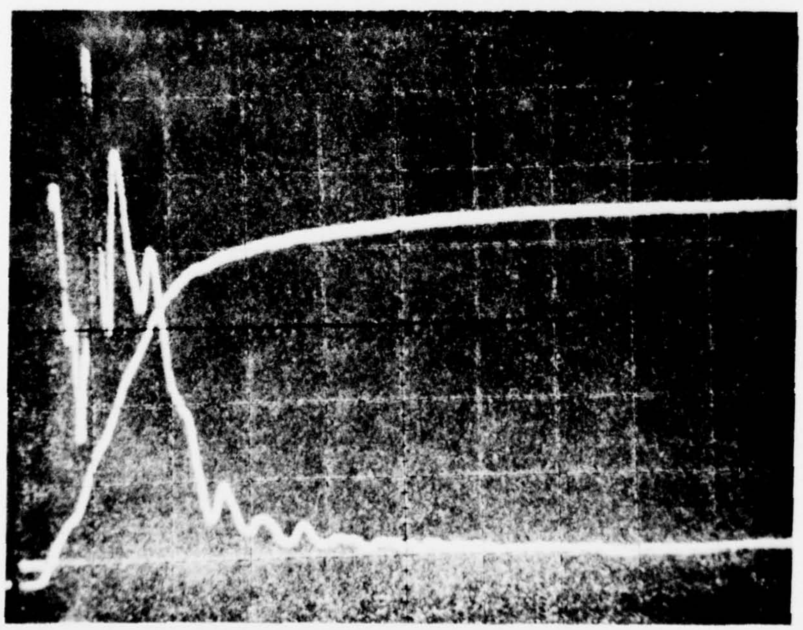


Figure 6. Test results for weld specimens fractured in the fusion zone.

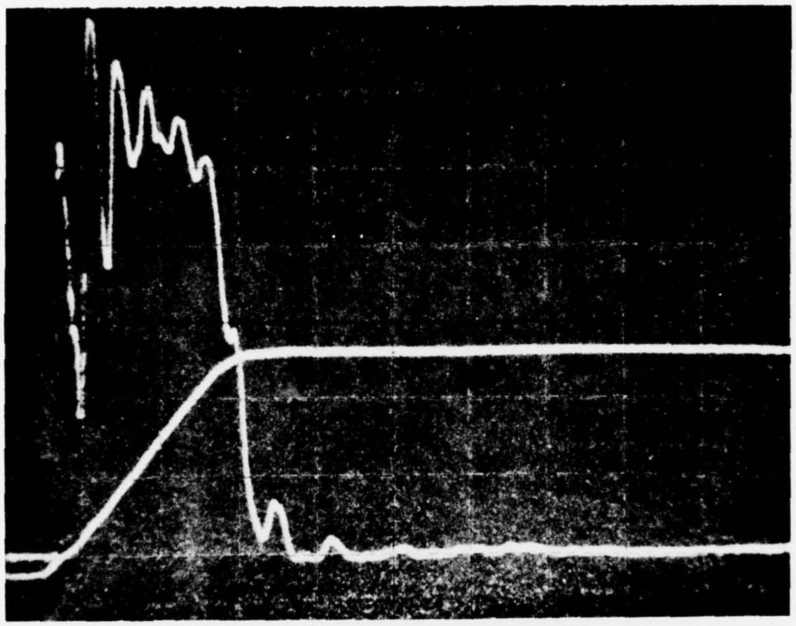
APPENDIX:
LOAD VS. TIME CURVES



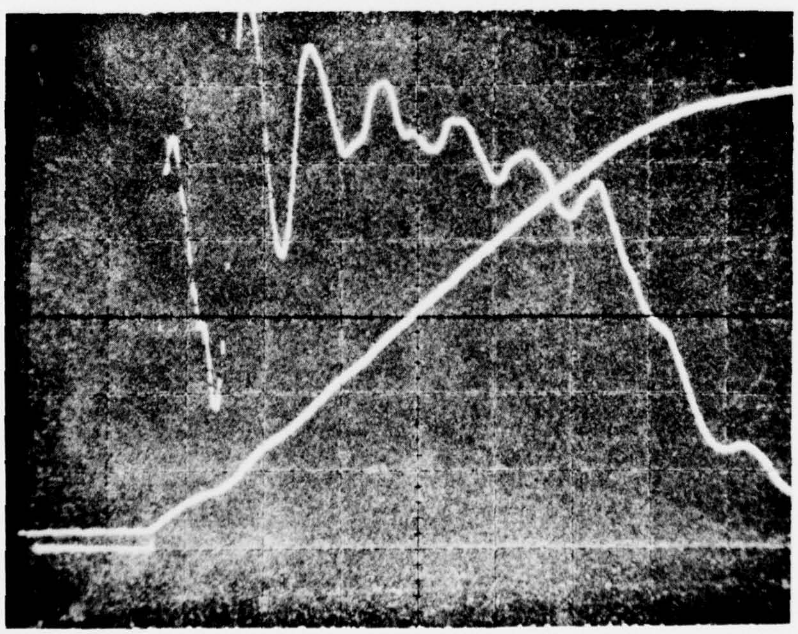
Specimen: A514F
Test Temperature: 21°C
Fracture Energy: 687 J
Load Scale: 17.8 kN/div
Time Scale: 0.2 ms/div



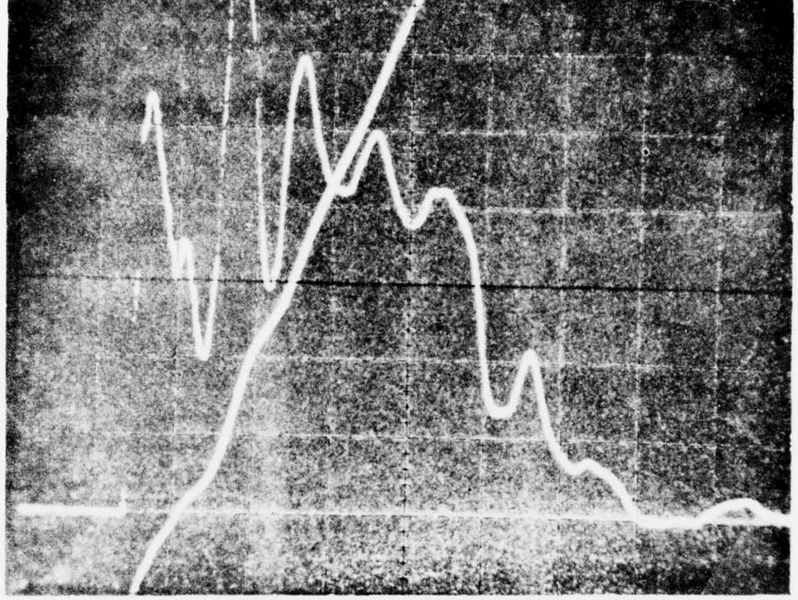
Specimen: COE-3
Test Temperature: 21°C
Fracture Energy: 593 J
Load Scale: 17.8 kN/div
Time Scale: 0.5 ms/div



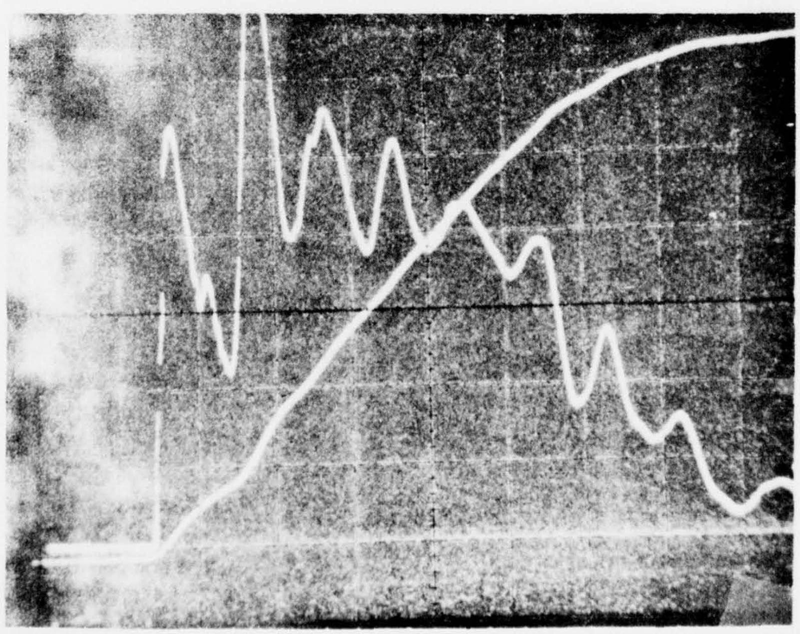
Specimen: H-4
Test Temperature: 21°C
Fracture Energy: 838 J
Load Scale: 17.8 kN/div
Time Scale: 0.5 ms/div



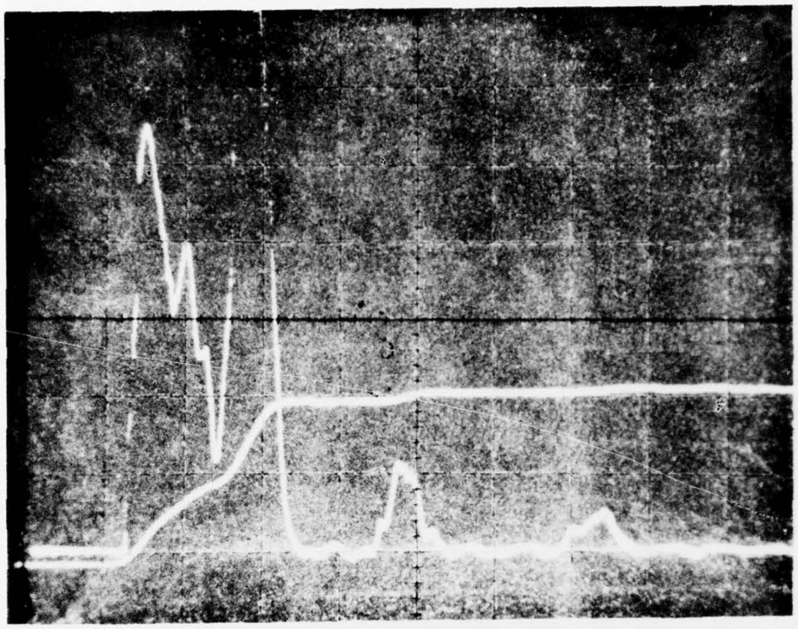
Specimen: H-8
Test Temperature: 21°C
Fracture Energy: 1064 J
Load Scale: 17.8 kN/div
Time Scale: 0.2 ms/div



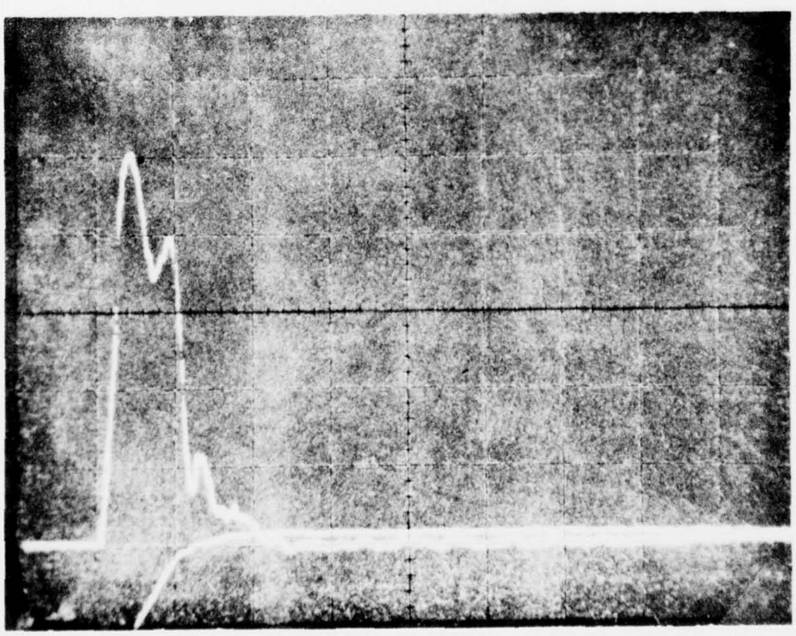
Specimen: H-3
Test Temperature: −40°C
Fracture Energy: 686 J
Load Scale: 17.8 kN/div
Time Scale: 0.2 ms/div



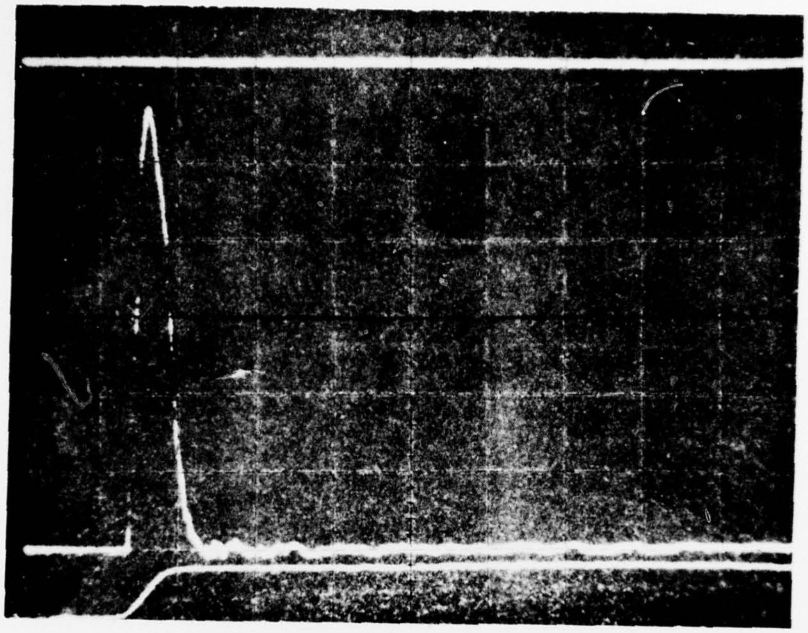
Specimen: H-9
Test Temperature: −40°C
Fracture Energy: 815 J
Load Scale: 17.8 kN/div
Time Scale: 0.2 ms/div



Specimen: H-1
Test Temperature: −60°C
Fracture Energy: 297 J
Load Scale: 17.8 kN/div
Time Scale: 0.2 ms/div



Specimen: H-7
Test Temperature: −90°C
Fracture Energy: 123 J
Load Scale: 17.8 kN/div
Time Scale: 0.2 ms/div



Specimen: H-6
Test Temperature: −140°C
Fracture Energy: 77 J
Load Scale: 17.8 kN/div
Time Scale: 0.2 ms/div

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